

SUSTAINED SPHEROMAK PHYSICS EXPERIMENT

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SSPX

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Sustained Spheromak Physics Experiment (SSPX)



Critical experiment to demonstrate energy confinement

Leads to a larger spheromak experiment to study control of the shift/tilt instabilities and of confinement on long timescales

The physics of the magnetic dynamo at high magnetic Reynolds numbers, relevant to astrophysical and other dynamos

New tools are available to address critical spheromak issues

Why the spheromak?



Important and interesting plasma and fusion science

- Robust equilibrium
- Helicity, magnetic dynamo, and magnetic turbulence
- Energy confinement in the presence of magnetic turbulence

A better MFE reactor than the tokamak

Optimal features are:

- Magnetic fieldlines contained in a toroidal volume
- No magnets through the hole in the torus
- No known physics or technology impediment to scaling to reactor

The spheromak meets these criteria

- Simple geometry for a less complex reactor
- Data from past experiments consistent with good core energy confinement, scaling well to a reactor

The base for a spheromak experiment



Site credits and new tools are available

Equipment and facilities from MFE experiments

- **DIID-D** (ongoing experimental collaboration) -- Modern data analysis, support from experimental team
- **Microwave Tokamak Experiment (MTX)** -- vacuum and power equipment, diagnostics, data acquisition and analysis
- **Mirror experiments** -- vacuum and power equipment
- **RACE** -- Capacitor bank, diagnostic racks isolated from ground, diagnostics

LLNL: Laboratory Directed Research and Development -- recent developments

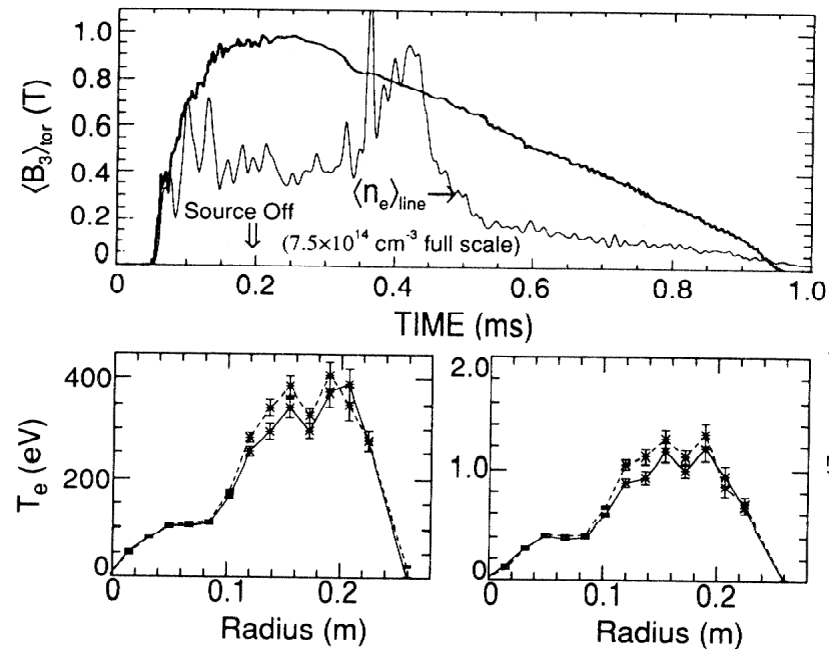
- DI in comprehensive computations (**CORSICA**) -- Design and data interpretation capability
- ER in **spheromak** -- Analysis of spheromak confinement, magnetic design, spheromak physics
- Lab-wide in **ultra-short-pulse reflectrometry** -- Basis for new magnetic field diagnostic



A sustained spheromak at high temperature

- **The dynamo during sustainment differs from that during decay**
 - During decay, the dynamo drives current on the (cold) edge as the core magnetic field drops
 - Magnetic turbulence opens field lines, allowing energy leakage
- **In a sustained spheromak, injected helicity propagates to the core**
 - Magnetic turbulence will still open field lines, allowing energy leakage
 - Because the core is hot, the required dynamo may be less than in decay
 - Wall and impurity effects are more difficult to handle than in decay

$T_e = 400$ eV in a decaying spheromak in CTX at LANL



GOALS OF THE SUSTAINED SPHEROMAK PHYSICS EXPERIMENT

Goal 1: Demonstrate high electron and ion temperatures



Demonstrate that electron and ion temperatures of a few hundred eV can be achieved in a spheromak plasma sustained by a magnetic dynamo (“helicity injection”)

- **This achievement will provide a “zeroth order” demonstration of good core energy confinement in a spheromak**
- **High electron temperatures have not been previously obtained in a sustained spheromak**
 - **Spheromak plasmas have been sustained for > 5 ms, but not with modern wall and vacuum conditions and with minimal field errors**
- **Temperature measurements will yield a “factor-of-two” evaluation of the electron thermal conductivity**

Goal 1: Experiments and Measurements



Required to demonstrate Goal 1:

Gun current, voltage; vacuum, etc.

Machine diagnostics

Electron density

Thomson scattering, interferometer

Electron temperature

Thomson scattering

Ion temperature

Spectroscopy of impurity (carbon) lines

Magnetic field

Magnetic probes

Goals 2 and 3: Energy confinement and magnetic turbulence



Goal 2: Relate energy confinement to the magnetic turbulence accompanying the dynamo and use this knowledge to optimize performance

Goal 3: Measure the magnetic field profiles and magnetic turbulence in the plasma and relate these to the science of the magnetic dynamo which drives the current in the plasma

- To address this fundamental physics problem in order to optimize confinement and to extrapolate performance to larger, long-pulse experiments
- New capabilities are available for critical measurements and for data analysis and interpretation
 - Magnetic field measurements in hot plasmas
 - Fast and comprehensive codes for modeling and data analysis

Similar capabilities have made major advances possible in tokamak physics and confinement -- we propose applying them to the spheromak

Evaluating energy confinement from data and analysis



Developments in diagnostics and comprehensive computations enable new experimental progress

- **New magnetic field diagnostics** will yield much better field profiles than edge probes alone
 - Previous experiments were insensitive to the central field, limiting magnetic field profile knowledge to a linear approximation

$$\frac{\mathbf{j} \cdot \mathbf{B}}{B^2} \approx \lambda_0 (1 + \alpha \psi) \quad (\lambda_0 \text{ and } \alpha \text{ are fit to the data})$$

This yielded inaccuracies in profiles, MHD stability, ohmic heating, etc.

New diagnostics are projected to yield profiles accurate to a few percent

- **CORSICA** combines MHD equilibrium calculations with transport and other physics to yield a comprehensive description of the plasma
 - The code is fast, permitting a much closer coupling to the experiment than previously possible

Goal 4: Beta limits



Demonstrate experimentally the pressure holding capability (“beta limit”) of the spheromak -- Achievable fusion power $\sim \beta^2$

- **Peak electron beta > 20% was observed experimentally (CTX) before a global instability caused loss of energy**
- **Confinement scaling deduced using the Fowler model predicted beta (~ stored energy) is limited by the magnetic fluctuation connection length**
 - **Lack of measurements of the fluctuation characteristics thus made separation of confinement and beta limit behavior difficult**

Experiments using our new diagnostics will be performed varying power and fueling, comparing the achievable beta with the magnetic field fluctuation characteristics

In addition, theory predicts sensitivity to the flux conserver shape; variation of the shape may be used to further evaluate the limits

Goal 5: Transition to equilibrium supported by external coils



Understand the initial phases of the transition of the plasma from an equilibrium supported by a magnetic-flux conserving wall to one supported by external coils

- A long-pulsed experiment will rely on external magnetic fields to support the equilibrium
 - A global mode (tilt/shift) is predicted to be unstable on the resistive time of the flux conserver
 - These modes are observed on fast time scales in the absence of the flux conserver
- Modeling of the feedback control of this mode can be done in parallel with the experiment (possible collaboration with GA)
 - Demonstrating active control will be a major goal of the follow-up experiment
- We propose to obtain **an initial comparison between theory and experiment by operating with a resistive flux conserver** to determine the characteristics of the instability on the slow timescale

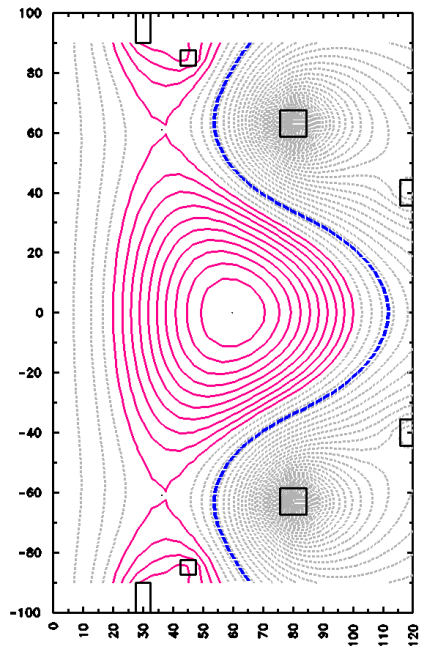
EXPERIMENTAL PLAN

MHD equilibria from CORSICA



CORSICA has been run to yield MHD equilibria and to model transport in the resulting magnetic field

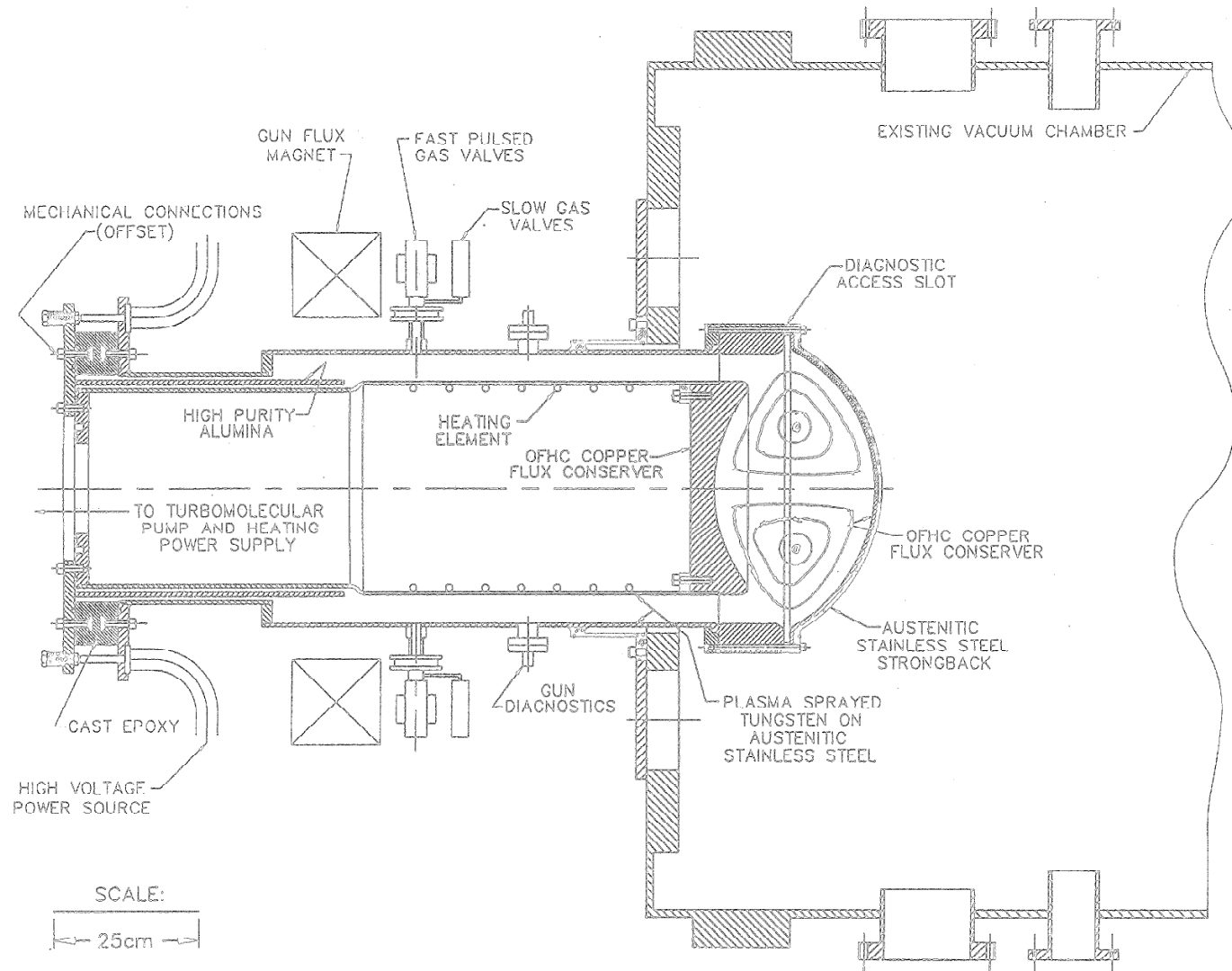
Detailed magnetic design of SSPX will be made



- **MHD equilibrium** using CORSICA
- **MHD stability** evaluated using the GATO code (General Atomics)
- **Conducting shell** to be placed on zero-flux surface as shown, replacing the external magnets used in the calculation
- **Helicity injection** from coaxial gun modelled by solenoids and current flow on open field lines

Preliminary gun and flux conserver design

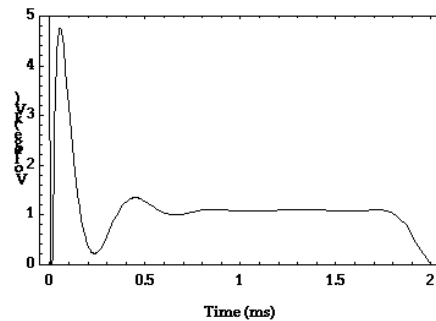




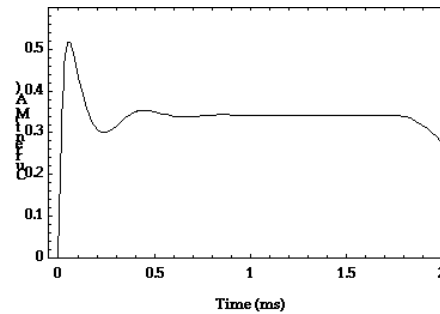
Plasma and system modeling predicts $T_e > 0.4$ keV



Voltage (kV)



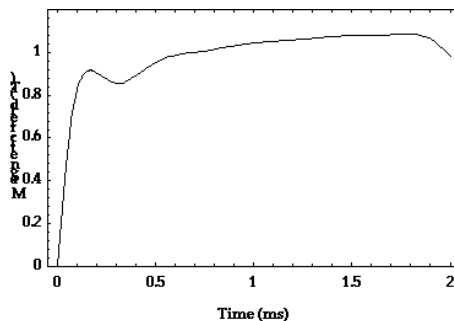
Current (MA)



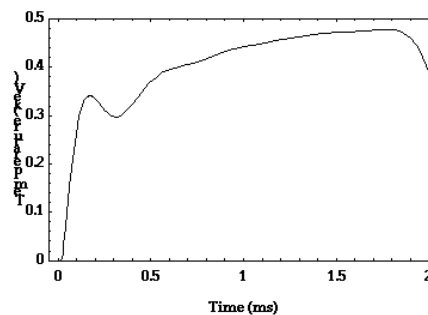
Plasma model with helicity injection and Fowler confinement (benchmarked against CTX)

$$\frac{dK}{dt} = 2\psi_g V_g - \frac{K}{\tau_k}$$

Magnet field (T)



Temperature eV



where K is helicity, ψ_g the gun magnetic flux, V_g the gun voltage, and τ_k the helicity decay time (capped at 0.5 ms)

Less conservative models yield $T_e > 1$ keV

Mechanical systems



- An existing **stainless steel vacuum vessel** (hard sealed) will replace the aluminum vessels presently in the facility
 - The significant reduction in outgassing and leaks will improve the vacuum by an order of magnitude
 - Additional vacuum systems will include turbo-molecular pumps, cryo pumps, and boron gettering of the flux conserver
- Three **solenoidal coils** will be installed around the vacuum vessel
 - These will be needed for later studies on the transition to long-pulse equilibrium
 - They may be activated earlier to provide a bias magnetic flux to minimize plasma-wall interaction

Vacuum conditioning must be an integral part of a new experiment



The best possible vacuum and wall conditions must be designed into a new experiment from the beginning

- Base pressure $\sim 10^{-8}$ torr
- Bakeout of gun and flux conserver to 200 - 300 C
- Discharge cleaning of the gun and flux conserver
- Gun electrodes coated with plasma-sprayed tungsten using a vacuum process
- Low-Z gettering (boronization) of the flux conserver

Data acquisition and analysis



- Acquisition will be **Camac based** with storage in a data base using a modular, distributed computer approach
- The system will be **accessible remotely** (for collaborators) and based on the **DIII-D data file format** so we can use existing software for the data base and data analysis
- Most of the **equipment is available from previous experiments**, but we plan to install a new master data computer to speedup the system
- Manpower requirements to bring the acquisition system into operation is estimated at **< 0.5 man year**



Diagnostics

- **An array of diagnostics will be installed to address the critical physics issues**
- **Collaborators will be invited to bring additional diagnostics to the experiment**

Task 1: Demonstration of high temperature, sustained spheromak

Machine diagnostics	voltage, current, etc	July 1997
Interferometer (mm)	density	July 1997
Thomson scattering	electron temperature	Jan 1998

Task 2: Study of confinement physics, the magnetic dynamo, and turbulence in the core of the sustained spheromak

Interferometers, magnetic probes	density, mag. fields	Jan. 1998
Bolometers	power radiated	Jan 1998
VUV spectroscopy	impurities	April 1998
VUV spectroscopy	T_i from ion Doppler width	April 1998
H-alpha	ionization	April 1998
Advanced diagnostics (complete)	magnetic field and fluctuations	Sept. 1998

New techniques to measure magnetic fields



Three techniques will be used to provide detailed spatial profiles and time history of the field

- **Wall probes** -- standard approach – straightforward but limited in spatial resolution
- **Ultra-short-pulse reflectrometry** -- combined O- and X-modes yield both density and magnetic field profiles
- **Transient Internal Probe (TIP)** -- a “snapshot” of the field profile, accurate to about 2% -- Developed by Tom Jarboe, et al. and used on HIT

TIP will provide benchmark for time-dependent measurements from wall probes and reflectrometry

Magnetic field measurements using ultra-short-pulse reflectrometry



- Ordinary mode waves propagating in from the edge reflect from the plasma cutoff -- $f = f_p$
- Extraordinary mode waves reflect at the cyclotron cutoff

$$f = \sqrt{f_p^2 + f_c^2/4} + f_c/2$$

- The use of both modes determines both the density profile and the magnetic field profile

